System Design for the Control of Liquid Helium by Electrostatic Forces for the Satellite lest of Equivalence Principle *Mission*

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A great.ly improved test. of the equivalence of inertial and gravitational mass is now possible, using superconduc ting measurement technology in an cart.h-orbitit-lg spacecraft., Since the equivalence principle is a fundamental postulate of Einstein's general theory of relativity, a precise test is of interest.

A liquid helium cryogen must be used to maintain the temperature of the four gravimeters at. 1.8 K. Because of the extreme sensitivity of the measurement, the gravitational disturbance caused by the motion of the liquid helium in the local gravity-gradi ent field is of concern. It is proposed to use electrostatic forces to provide the necessary cent-rol . We present. a description of the design and performance of a proposed flight System.

INTRODUCTION

Galileo and Newton assumed that, gravitation is a universal force which applies equally to all bodies in proportion to their masses, and that inertia] mass is proport.ions] to gravitational mass. From these assumptions, it follows that any two bodies will fall with equal accelerations in a gravitational field. Newton formulated this explicitly in his equations of motion:

$$f = m_g * g \qquad f = m_a * a \quad => \quad a = \left(\frac{m_a}{m_g}\right) * g$$

The assumption of equivalence is not obvious, and it. has been the subject of quest ion anti experime nt down to the present . (Fig. 1). Einstein made the bold post ul ate that. equivalence is a fundamental property of matter. Coupled with his equally bold postulate that the speed of light is a constant independent of the velocity of the observer, the equivalence principle leads directly to the Einstein's geometrical picture of gravitations a warping in space time.

The equivalence principle is known to be true to an accuracy of a part in 10^{11}. Why then should we remeasure such a precisely known quantity? There are several answers. Firstly, any quantity which is the basis of such a fundamental and precise theory as general relativity should be tested to the limits of current technique; secondly, quantum mechanics and general relativity in their present forms cannot both be true, and discovery of a deviation from the equivalence principle may point the way to a resolution of the paradox; and thirdly, certain nuclear forces may give rise to an apparent violation of the equivalence principle; precise measurements will help shape the theory of such forces.

Eotvos and later Dicke extended the accuracy of the measurement of eta, defined as

$$\eta = 2 * \frac{[m_j - m_a]}{[m_j + m_a]}$$

to about 1 part in 10^{-11} by the use of a new technology, the torsion balance. Dicke's measurements appear to have reached the limit possible in laboratory measurements; unavoidable gravitational and seismic noise can only be circumvented by completely new techniques.

THE STEP EXPERIMENT

The proposed measurement will be make use of four ultra-sensitive differential accelerometers on a satellite in a polar orbit at about 500 km. The instrument will be cooled to 1.8 K in a superfluid helium cryostat. The helium boil-off will be used to compensate drag. Superconducting quantum interference detectors will measure the relative displacement of the two masses of the differential accelerometer to about 10^{-13} cm.

The STEP experiment will extend the measurement of η to 1 part in 10^{17}. The improvement results from several factors; reduction of seismic noise by operation in a drag-free spacecraft; use of superconducting quantum interference detectors and superconducting bearings; and the use of phase detection at the signal frequency to reduce random and non-synchronous noise.

The measurement of η in space was proposed by P. Chapman in 1964, and by Worden and Everitt (Ref. 1, 2). This has resulted in several proposals for tests using a differential gravimeter in earth orbit. A proposal titled Satellite Test of the Equivalence Principle (STEP) was submitted to ESA by an American/European team for the second ESA moderate mission (M2), but lost out by a narrow margin. It is being reworked and resubmitted for the M3 mission by a largely European team for flight in 2005. Meanwhile, a Stanford-JPL team is leading an effort (QUICKSTEP) to fly a mission with reduced scope with NASA funding in 1999 or 2000.

HELIUM TIDES

A key feature of the orbital experiment is that the signal of the violation of the equivalence principle is at the orbital period of 6400 sec. See Fig. 2. A narrow-band filter will be used to remove disturbances except those at- the orbital period. One such disturbance results from the motion of the liquid helium in the gravity gradient field. As shown in Fig. 3, the gravity gradients drive the helium into a complex solid figure which rotates with respect- to t-he spacecraft at the orbits] frequency.

Any asymmetry in the location of the helium causes a gravitational disturbance which cannot. be separated from the equivalence principle! violation signal . Stated another way, t-he free surface of the superfluid helium must not be allowed to move more than a tort.ain amount.. The allowed motion is strongly dependent on the distance from the cent.er of mass of the differential accelerometer, as shown in Figure4.

ELECTROSTATIC SYSTEM

It is planned to eliminate the effect of the helium motions by controlling the locat.jell of the free surface by electrostatic forces. It is well known that. dielectrics experience a force in which is proportional to the square of the field gradient and in a direct-ion which moves it. into the region of strongest field. As shown in an earlier paper (Ref. 3), the expression for the equivalent acceleration is;

$$a = -\frac{1}{\rho}\left| \frac{\epsilon_0 E^2}{2} \times \nabla\epsilon_r + \frac{\epsilon_0}{6} \times \nabla\left[E^2 \times (\epsilon_r - 1) \times (\epsilon_r + 2)\right]\right|$$

where
ϵ_0 = dielectric constant of a vacuum = $4\pi*10^{-12}$
ϵ_r = relative dielectric constant = 1.05 for helium
ρ = density of liquid helium = 0.143 gm/cc

The first. term is proportional to the gradient. in the dielectric constant. Because the liquid helium is relatively incompressible, it is very small in the bulk fluid, but finite at the free surface between the gas and the liquid, where it acts like surface tension. The second term is a bulk term proportional to the gradient of E^2. The direction of the force is such that a liquid with a relative dielectric constant, greater than 1 will be driven into a region of converging fields.

The electrostatic system is shown in Fig. 5. It consists of a set of three electrodes in the helium tank, a power supply, and the necessary cables and high-voltage feed-throughs to connec _ the power supply to the elect-roclcs.

The electrode configuration is shown in Fig. 5. Three concentric electrodes are placed in the helium tank at. radii of 187 mm, ?50 mm and 300 mm. Electrode 2 is grounded, while electrodes 1 and 3 will be excited by the high voltage power unit..

The power unit_ contains four individual supplies each capable of delivering 10,000 volts at 1 micro-ampere , Each elect-rode is driven by two independent. supplies for redundancy. There are no high VOltage switches ; the power is switched by turning the low voltage input on and off. Each power supply is protected by a resistor. In case of a failure inside one supply, t-he redundant supply will be able to maintain the necessary voltage.

The key to the control of the helium is the placement of the free surface at. a distance of" more t-ban ?5 mm from the axis of symmetry. 10 accomplish this during the first. half of the mission, electrode 1 is excited, while 2 is kept grounded. The field configuration and free surf-ace are shown in Fig. 6. Approximately half-way through the mission, electrode 1 is grounded and electrode 3 is excited. The innermost. free surface is at. electrode 2, with a free surface between elect.rocles 2 and the tank wall . in each case , all f-ret surfaces lie outside the forbidden range.

TECHNICAL ISSUES

A. Breakdown and Arcing

There are three areas where breakdown may occur. The first is the cabling and feedthroughs bet.wcen the power supplies and the entry to the vacuum shell , In this region, the pressure varies from one atmosphere during ground testing to near-vacuum during operation in space. To avoid breakdown and arcing, the feedthroughs and cabling must be designed so that. the.re is no gaseous path between high voltage terminals and between high-voltage terminals and ground. In addition, special cabling with an extra ground shield must be used to prevent. charge build-up on the insulating cable covering, which would result. in arcing. (Ref. 4). Finally, the power supply must not. be operated in the transition region between 1 at, mosphere and vacuum to avoid any possibility of break-clown during launch.

The second is between the entry to the vacuum she]] and the entry to the helium tank . In this region there is always high vacuum once the vacuum is established. normal good high-voltage practice will avoid breakdowns. l'here are two special problems ; the cables and feedthroughs at. the helium tank must operate at cryogenic temperatures; and the cables must. be heat-sunk to the shields to minimize heat. leakage to the helium bath.

The third area is *internal* to the liquid helium tank. The pressure during cryogenic operations is that of' the saturated vapor pressure of liquid helium. It may be as high as 1 at.in when the helium is at 4.2 K or as low as 150 Pa at. 1.8 K. In helium, the breakdown is a function of' pressure. At 1.8 K the breakdown field is greater than 500 v/111.

To avoid breakdown several precautions must. be taken. These include careful design of the elect.rode configuration to minimize electric field, use of high voltage cable with added shield as described above, and elimination of sharp corners and edges.

ACKNOWLEDGEMENTS

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FIGURES

1, History of Experiments

? Test Mass Geometry and Expected Signal

3. He Distribution in Gravity Gradient

4. Allowed He motion

5. Electrostatic System and Electrode Configuration

6. Distribution of Liquid Helium in Orbit

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2. Worden, P. W. and C. F. W. Everitt, Satellite Test of the Equivalence Principle Science Requirements Document, Stanford University, Palo Alto, Calif., (1990)

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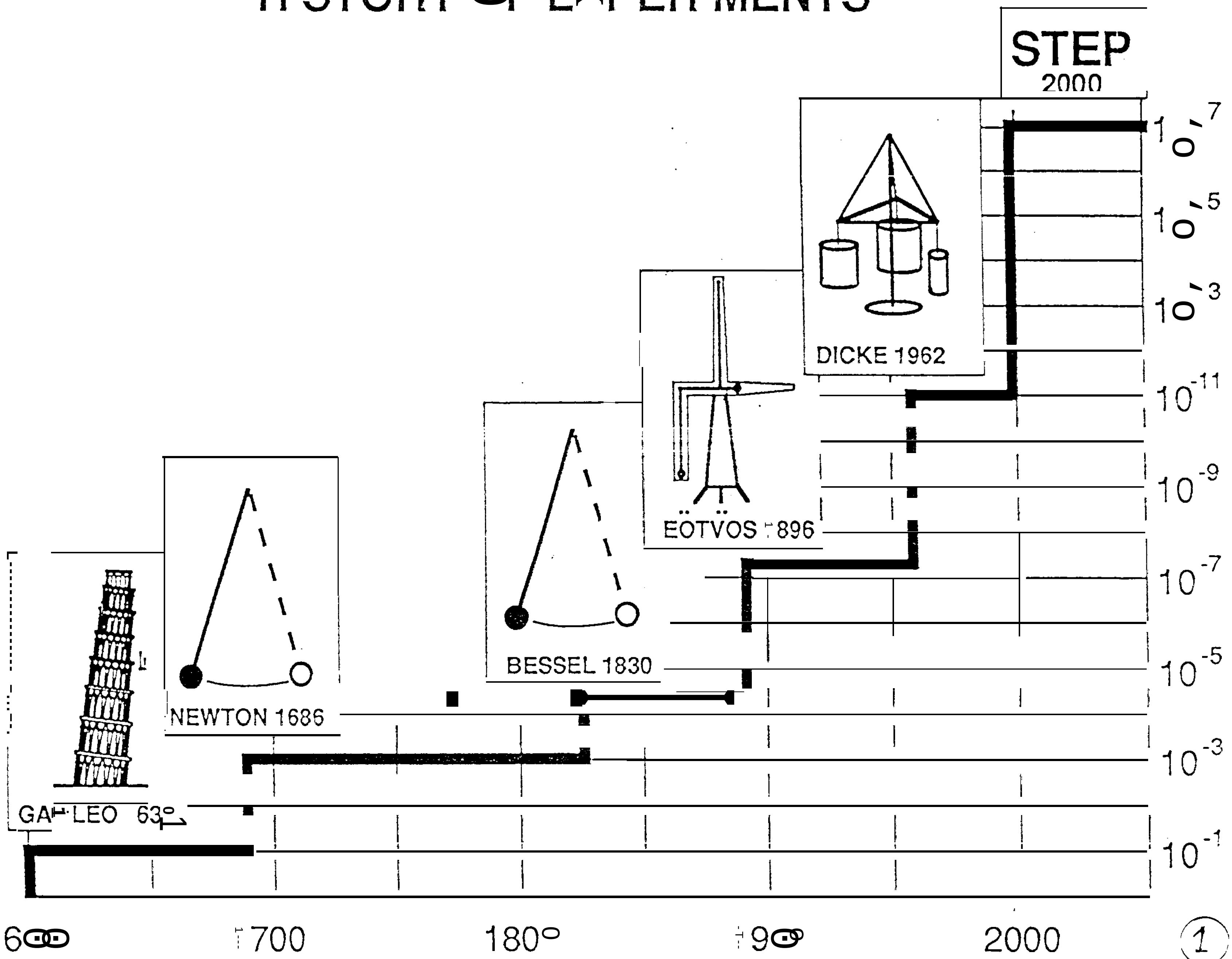
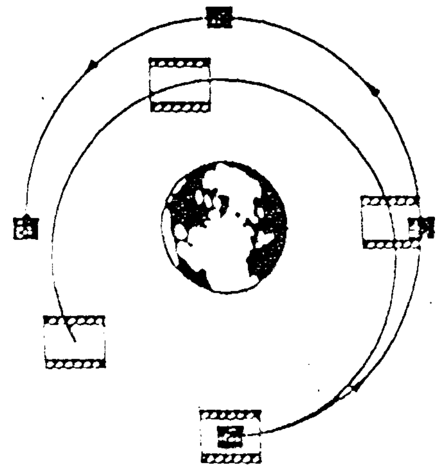
HISTORY OF EXPERIMENTS

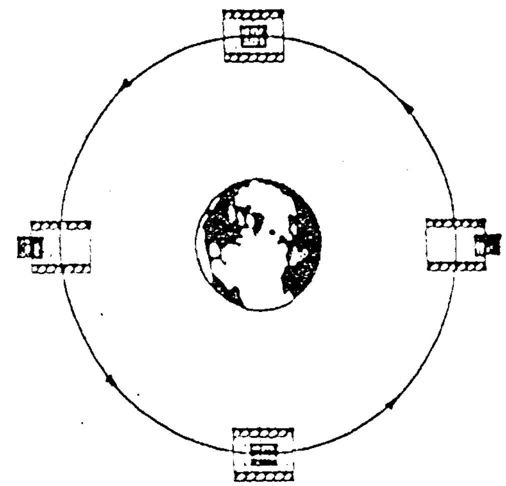


SATELLITE TEST OF THE EQUIVALENCE PRINCIPLE

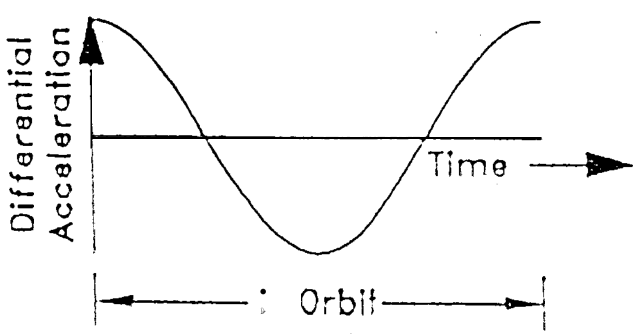
TEST MASS GEOMETRY



a) Free Masses

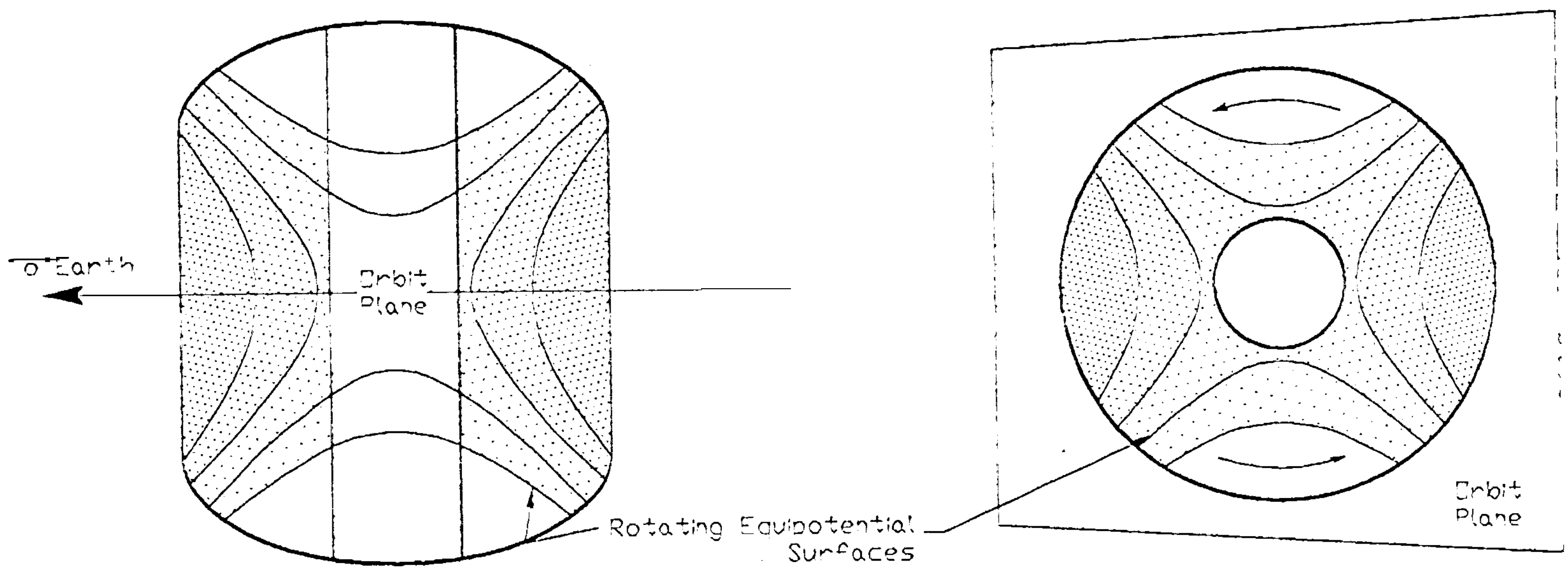


b) Constrained Masses



c) Signal of Violation

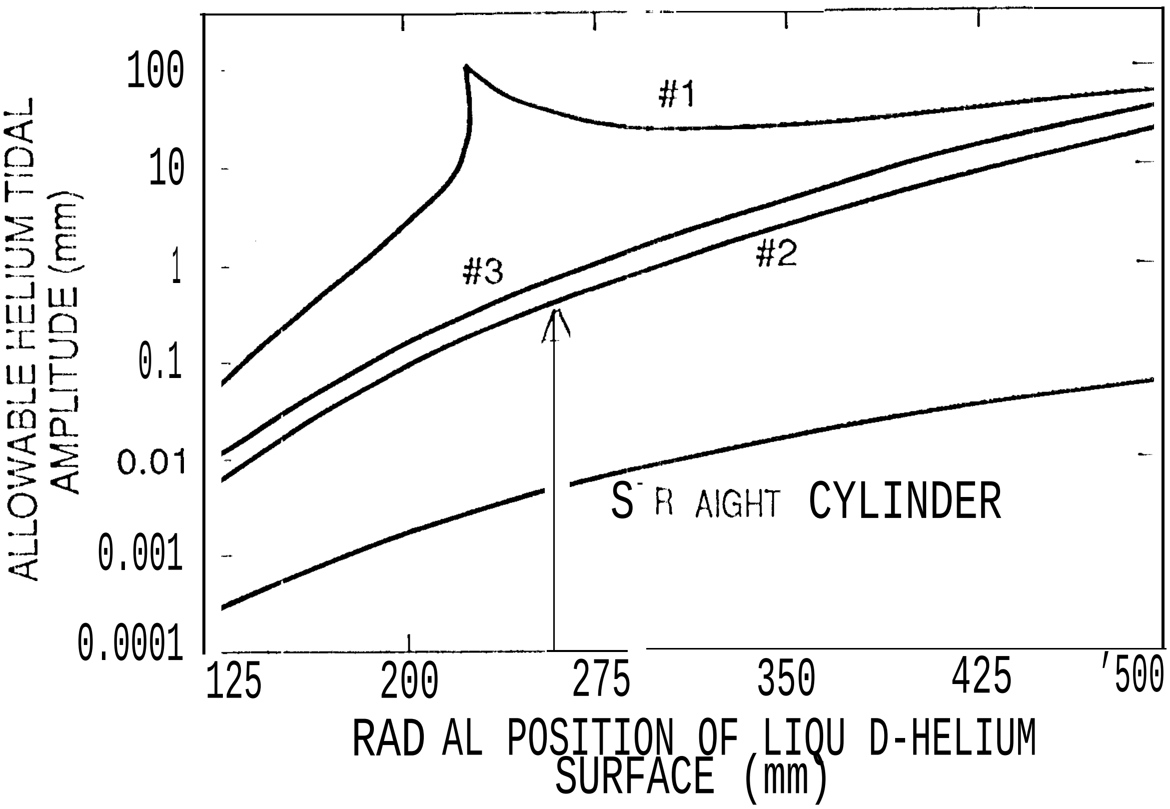
2

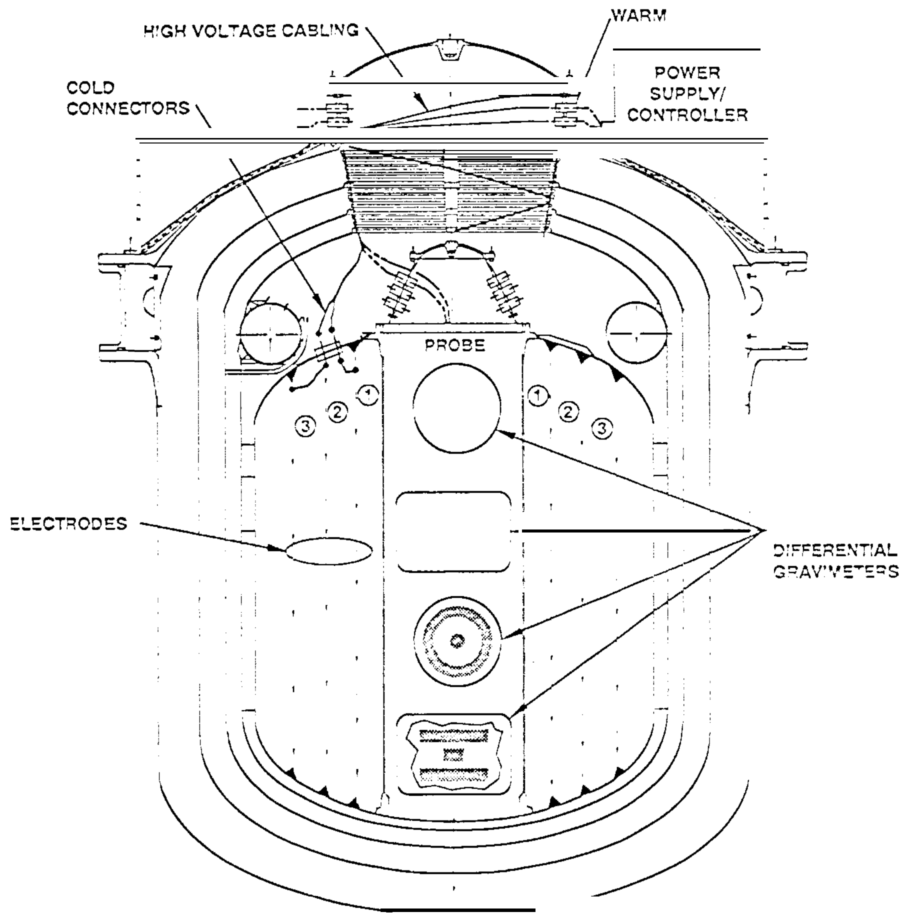


View parallel to orbit plane (red)

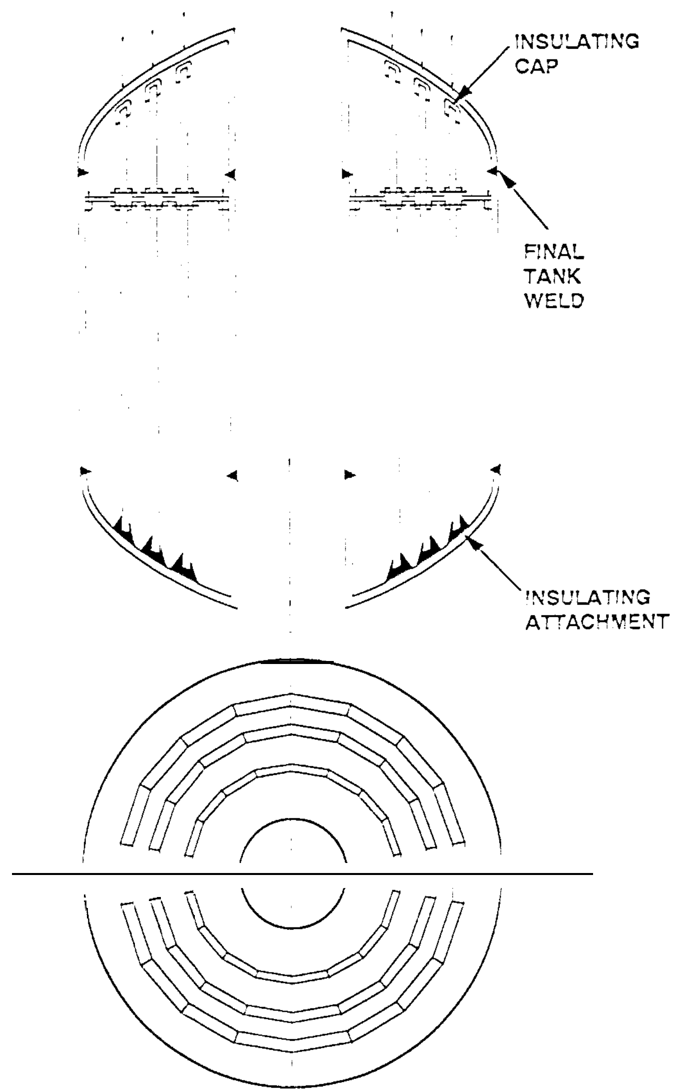
View normal to orbit plane

GRAVITY GRADIENT EQUIPOTENTIAL SURFACES
IN A NON-ROTATING SPACECRAFT

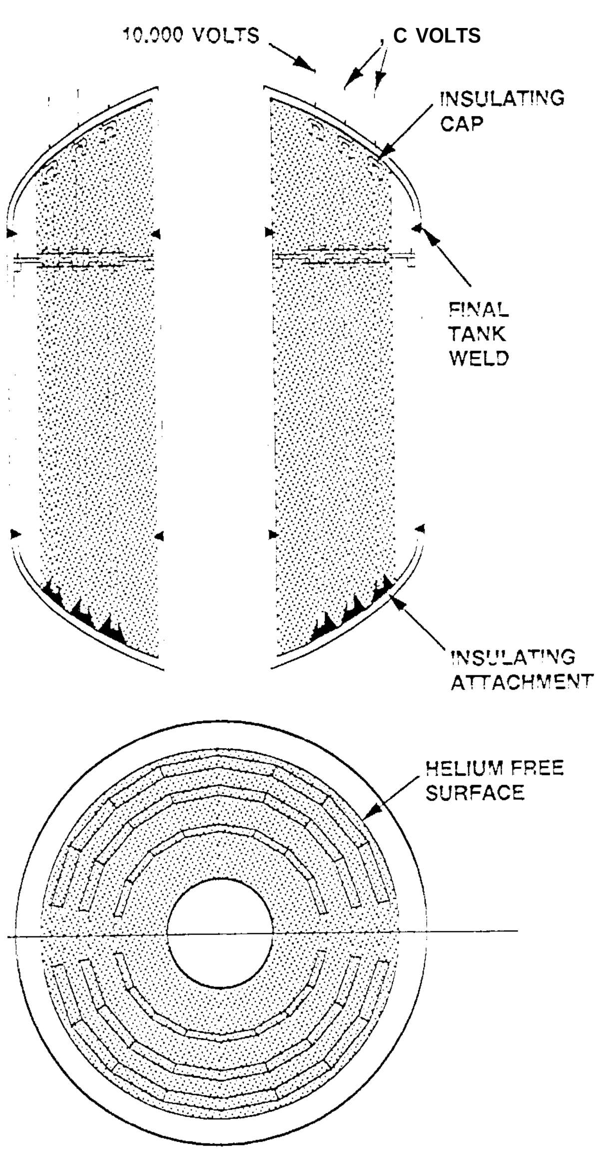

ALLOWABLE HELIUM TIDAL AMPLITUDE (mm)
100
10
1
0.1
0.01
0.001
0.0001
#1
#3
#2
S R AIGHT CYLINDER
125
200
275
350
425
500
RAD AL POSITION OF LIQU D-HELIUM SURFACE (mm)



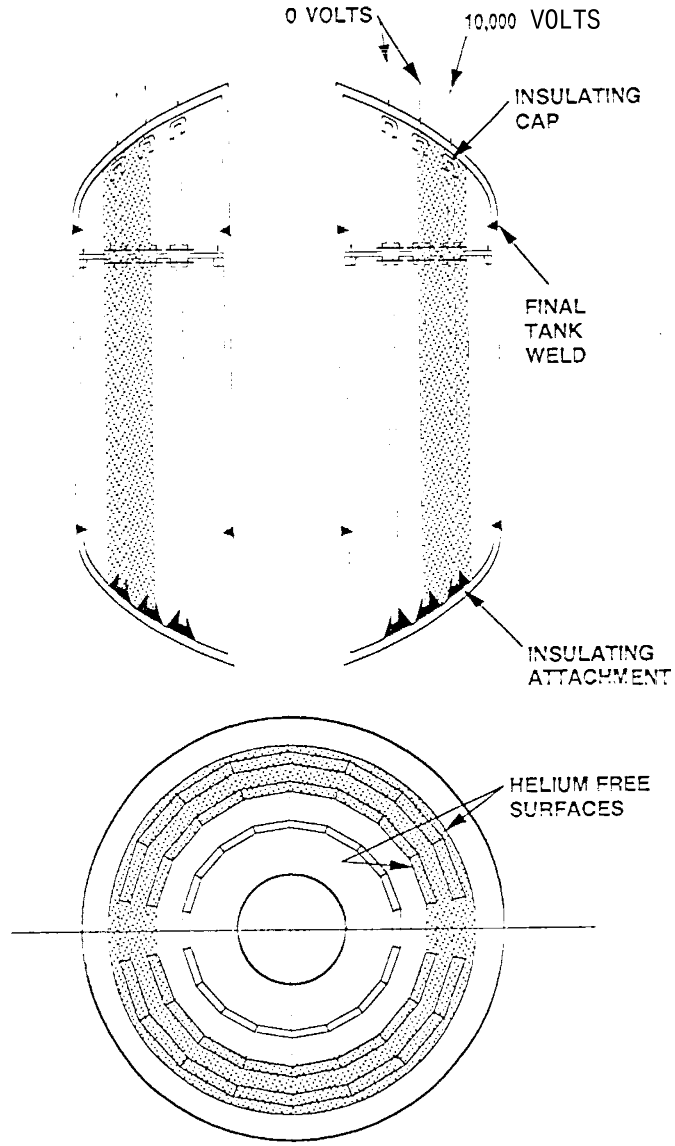
GRAVIMETERS AND
TIDAL CONTROL SYSTEM



ELECTRODE CONCEPT
18 IDENTICAL PANELS
3 SETS



FIRST HALF OF MISSION



SECOND HALF OF **MISSION**